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ASSESSMENT OF NOVELTY AND QUANTITY ACROSS DESIGN PHASES

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Abstract: Phase based design approaches are used in industry and many engineering projects for their various advantages, such as ease of management in designing complex products, better monitoring of updates of engineering projects, etc. A common division used in these is as follows: Task Clarification, Conceptual Design, Embodiment Design and Detail Design.

A wide body of research is available on design creativity, focusing on its nature in and effects on the two earlier phases of design. Further, much of creativity research is focused on the generation aspects of creativity. However, research rarely focuses on creativity, of the concepts, embodiments and details in a design process, in particular to understand how creativity of the outcomes evolve and progress from one phase to another. The focus of this paper is to apply existing metrics of creativity on case studies of design processes to understand the flow of creativity in a design process from one phase to another.

Keywords: *creativity, metric, concept, embodiment*

1. Introduction

Phase based design approaches provide several advantages, such as easy management of design of complex products, better monitoring of updates of engineering projects, etc. (French 1985, Hale and Gooch, 2004). Therefore, this approach is widely used in design community as well as in design research community. One of the most commonly used phase based approaches, by Pahl and Beitz (1984), divides the design process into task clarification, conceptual design, embodiment design and detail design. There are other design theories and models (e.g. French 1985, Hubka et al. 1988, Dieter and Schmidt 2009) which divide the design process into phases similar but not the same (See Table 1). In this paper, the definitions of the concept and embodiment as in Pahl and Beitz [1984] are adopted.

Table 1. Outputs of conceptual and embodiment phase

	Output of conceptual design	**Output of embodiment design**
French (1985)	Schemes	Assembly drawings or General arrangement drawings
Pahl and Beitz(1984)	Principle solution	Dimensional layout
Hubka et al(1988)	Concept	Laying out
Dieter and Schmidt (2009)	Concept	Full scale working prototype

The overall aim of design research is to improve the chances of producing a successful product by making designing more effective and efficient (Blessing & Chakrabarti, 2009). Innovation is one of the key factors that positively influence product success. Management of Creativity is essential for effective management of Product Innovation (Cropley et al. 2013). Cropley et al. (2013) also argue that effective management of creativity requires a means for measuring product creativity.

Numerous metrics have been proposed to evaluate various indicators of creativity rather than creativity directly (Howard et al. 2008). A large body of research exists on design creativity, particularly on its generational aspects in the earlier two design phases (Snider et al. 2013). However, research rarely focuses on the later phases of the design process, especially on evaluation of creativity across concepts, embodiments and details in a design process, so as to understand how creativity evolves and progresses from one phase to another. The focus of this paper is to use existing metrics for assessing creativity of design outcomes from case studies of design processes so as to understand the flow of creativity from one phase to another in a design process. The goal is to understand how well creativity is practiced across design phases, and where there is scope for improvement.

2. Hypothesis and Research Approach

The following hypotheses are developed to capture the evolution of creativity in design outcomes as the design process progresses from task clarification to conceptual design to embodiment design:

1) As design progresses from earlier to later phases, the number of solutions explored decreases. This is based on the assumption that as design progresses, the amount of information in a solution also increases, making it difficult for a designer to explore as many solutions as in the earlier phases.

2) As design process progresses from earlier to later phases, novelty of solutions remain the same. This is based on the assumption that novelty of new solutions (i.e. how different new solutions are from the existing solutions) developed in the earlier phase will be transferred from concept to embodiment to detail, and that the later phases currently contribute little to novelty.

The following research approach is used:

a) Review literature to identify the various metrics available for assessing creativity (especially novelty) at different phases of design.

b) Test whether it is possible to assess novelty of concepts and embodiments, from case studies collected from literature.

c) Apply appropriate measures for assessing novelty to test the hypotheses.

3. Creativity

Assessment of creativity has been explored in some detail in two domains: psychology and design research. In Howard et al. (2008) a comprehensive survey of creativity metrics has been reported based on three factors: originality (novel, original, new), appropriateness (appropriate, useful, purposeful, value, meaningful, tenable, satisfying) and third element (Unobvious, Adaptive, Leap, Change, Unexpected, Communicated, Transformation, Comparisons, Resourceful). However, Howard et al. (2008) do not provide methods or procedures for measuring creativity or its indicators.

One of the earliest research attempts on creativity metrics for engineering designs, by Shah et al. (2003), considered four indicators for creativity: novelty, variety, quality and quantity. The survey on the creativity metrics carried in our paper has been based on these four factors to widen the search of creativity, yet be specific on the definition of the factors (See Table 2). In the extra column any other factors considered by the authors is shown.

Shah et al. (2003) also provided equations to compute the four indicators for creativity: novelty, variety, quality and quantity. To compute Overall Novelty for an idea with m functions or attributes and n phases, the following equation is proposed to be used:

$$M_1 = \sum_{j=1}^{m} f_j \sum_{k=1}^{n} S_{1jk} p_k \quad (1)$$

This equation can be used to compute novelty scores of solutions at various phases of design.

Shah et al. (2003) proposed Variety to be computed using the following equation:

$$M_3 = 10 * \sum_{j=1}^{m} f_j \sum_{k=1}^{n} S_k b_k / M_{3max} \quad (2)$$

M_{3max} is the is the maximum possible variety score for the number of ideas in the set. The maximum score would be obtained if all ideas used different physical principles. Thus, M_{3max} is total number of ideas times 10. Therefore, (2) reduces to

$$M_3 = \sum_{j=1}^{m} f_j \sum_{k=1}^{4} S_k b_k / n \quad (3)$$

Quality is proposed by Shah et al. (2003) to be computed using the following equation:

$$M_2 = \sum_{j=1}^{m} f_j \sum_{k=1}^{2} S_{jk}\, p_k / n * \sum_{j=1}^{m} f_j \quad (4)$$

where
f_j is weights assigned according to importance of each function or characteristic,
S_1 is the novelty score assigned to each idea against a function or an attribute. It's value depends on the approach used: a priori or posteriori,
S_k is the score for level k,
S_{jk} is the score for quality of function j at level k,
p_k is weight assigned based on the importance of phases's importance,
b_k is the number of branches at level k,
m is the total number of functions, and
n is the total number of ideas.
However when solutions from only one phase is evaluated b_k=n since the number of branches is equal to number of ideas, equation (3) simply reduces to equation (5),

$$M_3 = \sum_{j=1}^{m} f_j S_k \quad (5)$$

As can be seen from the equation, the score heavily depends on the weights assigned to the phases rather than characteristics of the solutions, making the equation redundant to measure the variety scores of the solutions at different phases.
Considering novelty as the major indicator of the creativity, Chakrabarti & Khadilkar (2003) developed a detailed procedure to measure novelty. However, the procedure is applicable to products only. Chakrabarti (2006) proposed novelty, purposefulness and resourcefulness as the key indicators of the creativity. This work did not provide a method or procedure to measure either creativity or its indicators. Sarkar & Chakrabarti (2007) used novelty and usefulness as the umbrella indicators of creativity and have developed procedures to measure each. The procedure is applicable to both products and ideas. Srinivasan & Chakrabarti (2010) used novelty and variety as two related indicators of creativity and proposed procedures to measures novelty and variety of products, ideas and concepts. Pal & Chakrabarti (2014) developed a procedure to measure variety of ideas. In all of the above research, quantity is also considered as a common indicator of creativity.
Lopez-Mesa et al. (2011) used quantity, novelty (non-obviousness and newness), variety and feasibility as the criteria for evaluating the effectiveness of idea-generation methods.
Maher & Fisher (2012) proposed novelty, value and surprise as the indicators of creativity, and developed methods to evaluate each, for assessing products.
Oman et al. (2013) developed Comparative Creativity Assessment (CCA) and Multi-point Creativity Assessment (MPCA) based on modifications to the Shah et al (2003) metrics.

3.1 Overall conclusions from Literature Survey

The following conclusions were made from the literature on metrics for creativity:
a) There are many indicators of creativity, such as novelty, usefulness, originality, quantity, etc. However, novelty, quantity, and variety are the most recurring ones among them.

b) Chakrabarti and Khadilkar (2003), Shah et al. (2003), Sarkar and Chakrabarti (2007), Srinivasan and Chakrabarti (2010), Pal and Chakrabarti (2014),and Maher and Fisher (2012) have developed various procedures to measure various indicators of creativity.

a) Shah et al. (2003), Chakrabarti and Khadilkar (2003), Srinivasan and Chakrabarti (2010) have developed various procedures to measure novelty.

b) Shah et al. (2003) and Pal and Chakrabarti (2014) have developed procedures to measure variety.

c) Quantity is one of the simplest indicators for creativity and can be measured easily if one disregards in which phase the ideas have been developed.

Among the different metrics listed in Table 2, all the metrics with which one can measure the indicators for ideas can, in theory, be used to measure solutions at the end of each design phase. In this paper, metrics proposed by Shah et al. (2003) metrics have been used.

Table 2. Factors of creativity

	What can be assessed?	Novelty	Variety	Quantity	Quality	Other factors
Shah et al (2003)	Ideas	Y	Y	Y	Y	-
Chakrabarti &Khadilkar(2003)	Products	Y	-	Y	-	-
Chakrabarti (2006)	Products	Y	-	Y	-	Purposeful, Resourceful
Sarkar & Chakrabarti (2007)	Products and ideas	Y	-	Y	-	Usefulness
Srinivasan & Chakrabarti (2010)	Products, Concepts, ideas	Y	Y	Y	-	-
Pal & Chakrabarti (2014)	Ideas	-	Y	Y	-	-
Maher & Fisher (2012)	Products	Y	-	-	-	Value, Surprise
Lopez-Mesa (2011)		Y	Y	Y	-	Feasibility
Omen et al. (2013)	Ideas	Y	-	-	Y	CCA, MPCA

4. Data Collection

Hubka et al.(1988) in their book "Practical studies in systematic design" presented eight case studies; these case studies are used as the source for design data in the current study, for the following reasons:

a) The entire design process is covered in each of these case studies,

b) Data is provided for each of these phases: task clarification, conceptual design, embodiment design.

c) The data presented has sufficient detail to assess creativity of the solutions, i.e., at the end of each phase the solutions (concepts, embodiments) are given (both as textual explanation and drawings).

However, there are certain limitations of using the above data; for instance the morphological matrix of possible solutions provided shown is not complete, detail drawings have not been presented, etc.

Out of the eight case studies, Case study 6 (Tea Brewing Machine) has not been considered since the authors have presented only 3 out of the 7 alternative embodiments produced in this study, making it impossible to analyse the entire set of embodiments

In Case study 3 (on Powder-Coating Machine), the development of not the entire machine, but that of one of its sub-systems, Press Chamber Sub-system, starting with function structures until preliminary layout development, has been presented in full detail. Hence, we have analysed development of the Press chamber sub-system rather than the entire Powder-Coating machine.

5. Results and Discussion

5.1. Assessment of Quantity

The number of concepts and embodiments in each case study are computed using the definitions of concepts and embodiments by Pahl and Beitz (1984). The numbers are computed as follows:

1) Initially, all or almost all the functions and requirements to be satisfied by the system are enlisted.
2) A concept should satisfy all the requirements listed. Therefore a solution at system level that satisfies all the listed requirements is identified as a concept.
3) An embodiment is identified as the solution at system level which satisfies all the requirements and also satisfies the definition of an embodiment proposed by Pahl and Beitz (1984, 2007).

An example from Case Study 1 (CS1) is given here. In CS1, 8 functions are enlisted by the designer who then produced different ideas for each of these functions (see Figure 1.10 containing the morphological chart in Hubka et al (1988); it cannot be reproduced here due to space constraints and copyright issues). In the next step, the designer consolidated the ideas for the 8 functions to generate different concepts (refer to Figures 1.11 to 1.18 in Hubka et al. (1988)), which satisfy all the 8 functions. These are counted as concepts for the following reasons: (a) they satisfy all the functions, and (b) the solution is at the system level. After the concepts are generated, designer evaluated these concepts to select three among the eight (refer to Figures 1.22, 1.23, 1.24 in Hubka et al. (1988)) for developing into preliminary layouts. Then, out of these three preliminary layouts, designer further evaluated and selected two for developing dimensional layouts (refer to 1.25, 1.26 in Hubka et al (1988)). The preliminary layouts and dimensional layouts are counted together as embodiments.

5.1.1. Results

The number of outcomes in each phase in a case study is computed by counting the concepts and embodiments in the case study. Table 3 shows the number of concepts and embodiments produced in each case study.

Table 3. Assessment of Quantity

Case Studies	Concepts	Embodiments		
		Preliminary Layouts	Dimensional layouts	Total no. of embodiments
CS1	8	3	2	5
CS2	6	2	2	4
CS3	3	1	0	1
CS4	1	0	0	0
CS5	6	3	2	5
CS7	1	0	1	1
CS8	5	0	2	2

5.1.2. Discussion

As can be seen from Fig. 1, the first hypothesis "the quantity of solutions produced decreases as phase increases" is confirmed. In Case study 4 on development of a P-V-T apparatus, the designers carried out rough form-determination for only a few of the sub-systems. There were no preliminary layouts or dimensional layouts developed in the end; hence the number of embodiments developed is shown as zero.

5.2. Assessment of Novelty

If novelty is assessed at a single design phase, k=1, and p_k (i.e. weights based on the importance of the phases) is not given. Thus, equation (1) reduces to the following:

$$M_1 = \sum_{j=1}^{m} f_j S_{1j} \quad (6)$$

Evaluation of novelty involves measuring two variables f_j and S_{1j}. While f_j is assignment of values to the functions based on the importance of functions, S_{1j} reflects the score of the solutions (concepts or embodiments) and is assigned using a-priori method. In this method, the score is assigned to each individual idea in the concept for a particular function. An example is given from CS1 (see Table 4). First, the functions are assigned the score f_j based on their importance. Then each idea used in a concept is rated (S_{1j}) based on the set of ideas developed by the designer in that particular design session. Using Equation (6), one can calculate novelty scores of each solution (concept or embodiment). Once the novelty scores of all the solutions at a particular phase is calculated, the average of all the scores is taken as a measure of the novelty score for that phase of design.

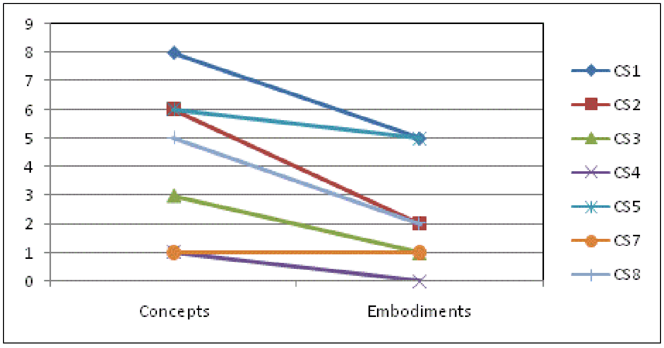


Figure 1. Quantity at various phases of design process

Table 4S_{1j} scores assigned to each ideas for respective functions

Functions	F1	F2	F3	F4	F5	F6	F7	F8	**M1**
fj	0.2	0.15	0.2	0.1	0.05	0.05	0.05	0.2	
Concept1	3	3	7	3	3	3	3	3	3.8
Concept2	3	7	7	10	3	3	0	3	4.95
Concept3	3	3	7	3	3	3	3	3	3.8
Concept4	3	3	3	3	3	3	3	3	3
Concept5	3	3	3	3	3	3	3	3	3
Concept6	3	3	10	3	3	10	10	3	5.1
Concept7	3	7	3	3	3	10	10	3	4.3
Concept8	7	3	3	3	3	3	10	3	4.15
Embodiment1	3	3	3	3	3	3	3	3	3
Embodiment2	3	3	3	3	3	3	3	3	3
Embodiment3	7	3	3	3	3	3	10	3	4.15
Embodiment4	3	3	3	3	3	3	3	3	3
Embodiment5	7	3	3	3	3	3	10	3	4.15

As seen from Table 4, Concepts 5, 6 and 8 correspond to Preliminary layouts (embodiment1, 2 and 3). In the embodiment stage, only further detail was added to the solutions, and the focus was not on increasing the novelty of the ideas. Hence the ideas did not change and the scores remained as before.

5.2.1. Results

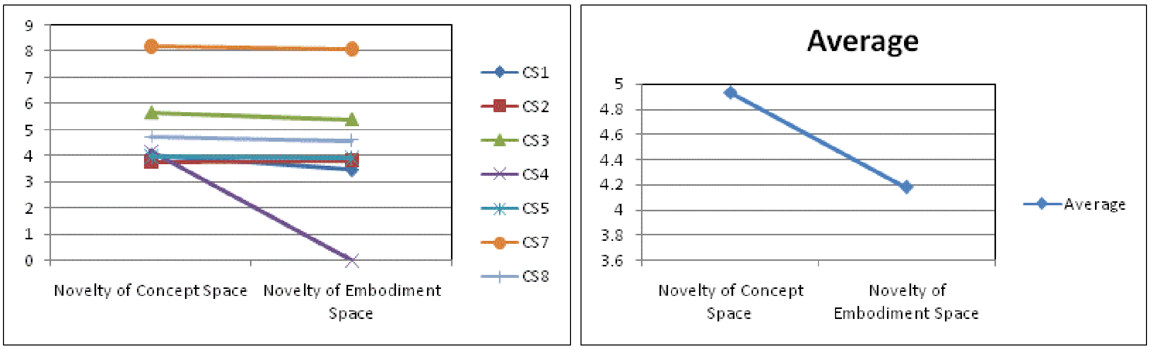
The novelty of the solution space at the end of each phase in a case study is calculated by identifying the concepts and embodiments in the case study, assessing their individual novelty, and averaging across all solutions developed in that phase. Table 5 provides the average novelty scores for concepts and embodiments produced for each case. In this metric, the length of the scale of measure is not fixed. The higher the number, higher the novelty of the solution and hence that of the solution space.

5.2.2. Discussion

As seen from Fig. 2a, the second hypothesis “the novelty of solutions produced as design process progresses will remain the same” seemed to have been refuted in the set of case studies considered.

Table 5. Assessment of Novelty

Case studies	Concepts	Embodiments
CS1	4.0125	3.46
CS2	3.76	3.8
CS3	5.67	5.4
CS4	4.16	0
CS5	3.98	3.9
CS7	8.2	8.1
CS8	4.73	4.575
Average	4.93	4.18



(a) (b)

Figure 2. (a) Novelty and **(b)** Average Novelty score across cases at various phases of design process

Novelty of solutions decreased as design progressed (see Fig. 2b). Possible reasons are the following:
(a) The novelty of a solution space depends on the novelty scores of individual solutions within the solution space.
(b) Selection of solutions depends on the decision making criteria used by the designers, i.e., if designers did not consider novelty as a criterion, high novelty solutions might not get selected.
(c) Typically, high novelty solutions also carry high-risk. Therefore, unless more effort is put in to embodying these, their embodiments are less likely to be feasible, and might get rejected early on.
It is also observed that, except for Case Study 2, novelty of concepts was consistently more than that of their embodiments. In Case study 2, out of the six concepts developed by the designers, three had high novelty scores (Novelty of Concept1, Concept3, Concept6 being 4, 3.6 and 6.6 respectively) and the other three lower novelty scores (Novelty of Concept2, Concept4 and Concept5 being 2.8, 2.8, 2.8). The average novelty score of the concept space was 3.76. Concept1 and Concept3 were selected by the designers to develop into embodiments; at the end of the embodiment phase, both the solutions, i.e., Embodiment1 and Embodiment2 retained their respective scores of 4 and 3.6. Thus, the average novelty score for the embodiment space was 3.8. As in the embodiment phase, the solutions neither increased nor diminished the novelty score, and the end result was that novelty of the embodiment space very slightly higher than that of the concept space.

Conclusions and Future Work

In this paper, different creativity metrics available in literature have been reviewed first to assess as to whether or not they would be suitable for measuring creativity of outputs in different phases of the design process. Among the metrics available, it was found that novelty metrics from Shah et al. (2003), Sarkar and Chakrabarti (2007), and Srinivasan and Chakrabarti (2010) can be used for evaluating novelty of outputs across phases. Metrics from Shah et al. (2003) are used for evaluation of novelty carried out in this paper. The metrics used are for novelty and quantity, the two most common indicators for creativity; these are applied to analyse the concepts and embodiments developed in the case studies expounded in the book "Practical studies in systematic design" by Hubka et al. (1988).

Analyses of outcomes from the case studies indicate that both the number and the average novelty of solutions explored decreased as design progressed from conceptual to embodiment phase. Reduction in the number of solutions developed at the later phase is understandably less, due to convergence towards one or fewer solutions, which is a generic characteristic of most design processes in practice.

We argue that the novelty of the solution space reduces as design progresses because the overall novelty of a solution space depends on the novelty scores of individual solutions within the solution space. Choice of individual solutions in the later phases of the design process depends on the selection criteria used by the designers, i.e., if designers did not consider novelty as a criterion, high novelty solutions would not necessarily be selected at the early phases. Further, high novelty solutions are typically high risk solutions and hence would have a greater likelihood of rejection.

In this paper only novelty and quantity are measured for the outputs from the case studies. In future, quality and variety also need to be measured, to better understand the decision making criteria of the designers, as to whether or not a high novelty solution would be carried over from conceptual design to embodiment design to final solution and why. Other metrics from literature will also be applied.

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